

# Repercussions of Flavour Symmetry Breaking on CP Violation in $D$ -Meson Decays

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Thorsten Feldmann,<sup>a</sup> Soumitra Nandi,<sup>a</sup> and Amarjit Soni<sup>b</sup>

<sup>a</sup>*Theoretische Elementarteilchenphysik, Naturwissenschaftlich Technische Fakultät,  
Universität Siegen, 57068 Siegen, Germany*

<sup>b</sup>*Physics Department, Theory Group, Brookhaven National Laboratory,  
Upton, NY 11973, USA*

*E-mail:* [thorsten.feldmann@uni-siegen.de](mailto:thorsten.feldmann@uni-siegen.de), [nandi@physik.uni-siegen.de](mailto:nandi@physik.uni-siegen.de),  
[soni@bnl.gov](mailto:soni@bnl.gov)

**ABSTRACT:** We investigate to what extent the recently measured value for a non-vanishing direct CP asymmetry in  $D^0 \rightarrow K^+K^-$  and  $D^0 \rightarrow \pi^+\pi^-$  decays can be accommodated in the Standard Model (SM) or extensions with a constrained flavour sector, for instance from a sequential 4<sup>th</sup> generation of quarks (4G). From the comparison with  $D^0 \rightarrow K^-\pi^+$  branching ratios, we establish large U-spin symmetry ( $d \leftrightarrow s$ ) breaking effects with large strong phases between different interfering amplitudes. On the basis of conservative estimates on amplitude ratios — which are supported by an analysis of the breaking of a  $c \leftrightarrow u$  symmetry in non-leptonic  $B^0$  decays — we find that, in the SM, direct CP asymmetries in the  $\pi^+\pi^-$  or  $K^+K^-$  modes (or in their difference) of the order of several per mille are still plausible. Due to the constraints on the new CP phases in the 4G model, only moderate effects compared to the SM estimates are possible. We suggest CP studies at LHCb as well as at (Super)B-factories of several distinctive modes, such as  $D^+ \rightarrow \bar{K}^{(*)0}\pi^+, \phi\pi^+$  and  $D_s \rightarrow K^{(*)0}\pi^+, \phi\pi^+(K^+)$  etc., which should shed more light on the short- and long-distance issues underlying CP violation in non-leptonic D-meson decays.

**KEYWORDS:** CP Violation, D-Meson Decays

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## 1 Motivation

CP-violation studies in the charm system are important for a variety of reasons. First, in the Standard Model (SM), only small asymmetries are expected, see e.g. [1–4] and references therein. On the other hand, in many models of new physics (NP), the top quark is sensitive to non-standard effects, and there are flavour-changing interactions which couple the charm and the top quark. Flavour models based on generic ideas of warped extra dimensions represent a very interesting example of this type; especially so as large  $\mathcal{O}(1)$  CP-odd phases may accompany the new interactions [5]. This is also the case in many models with an extended Higgs sector [6]. Even in a simple extension of the SM with a fourth generation of fermions, significant differences in CP asymmetries in the charm sector may arise as compared to the SM [7–9]. Furthermore, the charm-quark mass ( $\approx 1.2$  GeV) is not that heavy; consequently large (CP-even) rescattering phases can be present in  $D$ -meson decays which, together with CP-odd phases from the SM and/or NP sector, can lead to sizeable direct CP asymmetries. CP studies via  $D^0$ - $\bar{D}^0$  mixing are also highly motivated as the  $D^0$  is a unique bound state of charge 2/3 quarks and is thus sensitive to NP affecting the top quark.

In this article, we will be mainly concerned with CP violation in non-leptonic  $D^0$  decays. The time-integrated CP asymmetry  $A_{\text{CP}}(f)$  for a given final state  $f$  is defined as

$$A_{\text{CP}}(f) = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f)}, \quad (1.1)$$

which (to first approximation) may be decomposed as (see e.g. [10])

$$A_{\text{CP}}(f) = A_{\text{CP}}^{\text{dir}} + A_{\text{CP}}^{\text{ind}} + A_{\text{CP}}^{\text{mix}}. \quad (1.2)$$

Here,  $A_{\text{CP}}^{\text{dir}}(f)$  is the direct CP asymmetry in the decay  $D^0 \rightarrow f$ ,  $A_{\text{CP}}^{\text{mix}}$  is the CP asymmetry from  $D^0$ - $\bar{D}^0$  mixing, and  $A_{\text{CP}}^{\text{ind}}$  stems from the interference of mixing and decay. Recent results from the LHCb experiment [11] on CP asymmetries in  $D^0$  decays,

$$\Delta A_{\text{CP}}^{\text{dir}} \equiv A_{\text{CP}}^{\text{dir}}(K^+K^-) - A_{\text{CP}}^{\text{dir}}(\pi^+\pi^-) = -(0.82 \pm 0.21 \pm 0.11)\%, \quad (1.3)$$

indicate a  $3.5\sigma$  deviation from 0, with a large amount of experimental systematics cancelling in the considered difference of decay modes. We remind the reader that, in the  $SU(3)_F$  limit for light quarks [10], the direct CP asymmetries in the individual channels are equal in magnitude but opposite in sign,  $A_{\text{CP}}^{\text{dir}}(K^+K^-) \simeq -A_{\text{CP}}^{\text{dir}}(\pi^+\pi^-)$ . Assuming that the effects of  $A_{\text{CP}}^{\text{mix}}$  drop out in the difference, and that the effect of  $A_{\text{CP}}^{\text{ind}}$  is small, this points to a relatively large value for  $|A_{\text{CP}}^{\text{dir}}|$  for both decay modes. Not surprisingly, the LHCb result has renewed the interest in CP violation in charm physics, and a number of articles, addressing the interpretation of the data within the SM or NP, have appeared since (see e.g. [12–23]). At about the same time, the CDF collaboration has reported their result from an independent measurement [24], which also provides numbers for the individual CP asymmetries in the  $(K^+K^-)$  and  $(\pi^+\pi^-)$  channel,

$$\begin{aligned} A_{\text{CP}}(K^+K^-) &= (-0.24 \pm 0.22 \pm 0.09)\%, \\ A_{\text{CP}}(\pi^+\pi^-) &= (+0.22 \pm 0.24 \pm 0.11)\%, \end{aligned} \quad (1.4)$$

which is consistent with the above LHCb result. Both measurements dominate the world average provided by the HFAG collaboration [25],

$$\Delta A_{\text{CP}}^{\text{dir}} = (-0.645 \pm 0.180)\%. \quad (1.5)$$

Although a direct CP asymmetry of the order of a few per-mille seems to be a small number, the SM expectations for  $\Delta A_{\text{CP}}^{\text{dir}}$  in  $D$  decays are usually even smaller, because the only source of observable CP violation comes from the interference with a sub-leading amplitude which involves a relative suppression factor involving 4 powers of the Cabibbo angle. A precise quantitative estimate, however, is difficult because standard approximation methods known from  $B$ -meson or kaon physics do not seem to work sufficiently well in the charm sector, since the charm-quark mass is neither much smaller nor much larger than the typical hadronic scales. Without strong theoretical prejudices about non-perturbative hadronic dynamics, we are therefore constrained to semi-quantitative analyses. The related questions that we are going to explore in this paper are:

- What can be learned from U-spin relations between down- and strange-quarks, and how large is the effect of U-spin breaking?
- Do we have phenomenological evidence for large strong phases in  $D^0 \rightarrow P^+P^-$  decays, and how does this compare with the situation in non-leptonic  $B^0$ -meson decays?

- How large do sub-leading amplitudes in the SM have to be in order to explain the observed  $\Delta A_{\text{CP}}^{\text{dir}}$ ?
- To what extent can NP models with constrained flavour sector, like for instance a model with 4 fermion generations, enhance the theoretical predictions for  $\Delta A_{\text{CP}}^{\text{dir}}$  as compared to the SM?
- Can we identify other  $D$ -decay modes which should exhibit similar patterns of CP violation?

## 2 $U$ -Spin in Non-Leptonic $D^0 \rightarrow P^+ P^-$ Decays

Assuming  $SU(3)$  flavour symmetry for the strong interactions of light quarks, the contributions to the amplitudes for non-leptonic  $D$ -meson decays can be related. For our purposes, it will be sufficient to focus on a sub-group,  $U$ -spin symmetry, which acts on  $U$ -spin doublets  $(d, s)$  and which have been frequently used to analyse weak non-leptonic meson decays, see for instance [26–29].

Starting point is the weak effective Hamiltonian for  $c \rightarrow uq\bar{q}'$  transitions ( $q, q' = u, d, s$ ) which can be decomposed into a  $U = 0$  and  $U = 1$  part, as follows

$$\begin{aligned} H_{\text{eff}}(c \rightarrow us\bar{d}) &= - (V_{cs}^* V_{ud}) H_{U=1}^{(U_3=-1)}, \\ H_{\text{eff}}(c \rightarrow uq\bar{q}) &= \left( \frac{V_{cd}^* V_{ud} - V_{cs}^* V_{us}}{\sqrt{2}} \right) H_{U=1}^{(U_3=0)} + (V_{cd}^* V_{ud} + V_{cs}^* V_{us}) H_{U=0}, \\ H_{\text{eff}}(c \rightarrow ud\bar{s}) &= (V_{cd}^* V_{us}) H_{U=1}^{(U_3=+1)}. \end{aligned} \quad (2.1)$$

Here  $H_{U=1}$  only contains the current-current operators from tree-level  $W$ -boson exchange, while  $H_{U=0}$  also receives contributions from strong and electro-weak penguin operators. The important property to notice is that the  $U$ -spin singlet or triplet terms are multiplied by a single combination of Cabibbo-Kobayashi-Maskawa (CKM) elements. In the exact  $U$ -spin limit, the amplitudes for the related  $D^0$ -meson decays into two light charged pseudoscalar mesons<sup>1</sup> are thus described by only two independent complex amplitudes, which we denote by  $A_{U=0}$  and  $B_{U=1}$ ,

$$\begin{aligned} \text{U-spin limit:} \quad \mathcal{A}[D^0 \rightarrow K^- \pi^+] &= 2 V_{cs}^* V_{ud} B_{U=1}, \\ \mathcal{A}[D^0 \rightarrow \pi^+ \pi^-] &= (\lambda_d + \lambda_s) A_{U=0} + (\lambda_d - \lambda_s) B_{U=1}, \\ \mathcal{A}[D^0 \rightarrow K^+ K^-] &= (\lambda_d + \lambda_s) A_{U=0} - (\lambda_d - \lambda_s) B_{U=1}, \\ \mathcal{A}[D^0 \rightarrow K^+ \pi^-] &= 2 V_{cd}^* V_{us} B_{U=1}, \end{aligned} \quad (2.2)$$

where we have defined  $\lambda_d \equiv V_{cd}^* V_{ud}$  and  $\lambda_s \equiv V_{cs}^* V_{us}$ . From the Wolfenstein expansion of the CKM elements in powers of  $\lambda = \sin \theta_C \sim \mathcal{O}(0.2)$ , we infer that the decay  $D^0 \rightarrow K^- \pi^+$

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<sup>1</sup>We are restricting ourselves to charged mesons (with  $U = 1/2$ ) here, because in this way we only generate  $U = 0$  and  $U = 1$  final states which require a minimal set of independent amplitudes, once we allow for arbitrary  $U$ -spin breaking, see below.

is Cabibbo allowed (CA), the decays  $D^0 \rightarrow \pi^+\pi^-$ ,  $K^+K^-$  are singly-Cabibbo-suppressed (SCS) with  $(\lambda_d - \lambda_s) \sim \mathcal{O}(\lambda)$ , while the decay  $D^0 \rightarrow K^+\pi^-$  is double-Cabibbo-suppressed (DCS). Furthermore, the contribution of the  $U = 0$  amplitude to the decays  $D^0 \rightarrow \pi^+\pi^-$  and  $D^0 \rightarrow K^+K^-$  is suppressed by another 4 powers of  $\lambda$ , since  $\lambda_d + \lambda_s \sim \mathcal{O}(\lambda^5)$ , and therefore the decay rates should be equal, while the CP asymmetries from the interference of  $A_{U=0}$  and  $B_{U=1}$  should be tiny, as already mentioned above. However, the measured branching ratios (BRs) for the CA, SCS, DCS modes (experimental numbers are taken from [25] or [49], see also references to the original experiments therein)

$$\begin{aligned} \text{BR}[D^0 \rightarrow K^-\pi^+] &= (3.949 \pm 0.023 \pm 0.040 \pm 0.025)\%, \\ \text{BR}[D^0 \rightarrow \pi^+\pi^-] &= (0.1425 \pm 0.0019 \pm 0.0018 \pm 0.0014)\%, \\ \text{BR}[D^0 \rightarrow K^+K^-] &= (0.3941 \pm 0.0038 \pm 0.0050 \pm 0.0024)\%, \\ \frac{\text{BR}[D^0 \rightarrow K^+\pi^-]}{\text{BR}[D^0 \rightarrow K^-\pi^+]} &= (0.331 \pm 0.008)\%, \end{aligned} \quad (2.3)$$

do not follow the pattern expected from U-spin symmetry. Actually, correcting for phase-space effects and CKM factors, the following observables

$$\text{obs}_1 \equiv \frac{\text{BR}[D^0 \rightarrow K^+K^-]/|\vec{p}_K|}{\text{BR}[D^0 \rightarrow \pi^+\pi^-]/|\vec{p}_\pi|} \simeq 3.22 \pm 0.09 \quad (2.4)$$

$$\text{obs}_2 \equiv \frac{\text{Br}[D^0 \rightarrow K^-\pi^+]/|\vec{p}_{\pi K}|}{\text{Br}[D^0 \rightarrow K^+K^-]/|\vec{p}_K|} \lambda^2 \simeq 0.47 \pm 0.01, \quad (2.5)$$

$$\text{obs}_3 \equiv \frac{\text{Br}[D^0 \rightarrow K^+\pi^-]}{\text{Br}[D^0 \rightarrow K^-\pi^+]} \lambda^{-4} \simeq 1.28 \pm 0.03, \quad (2.6)$$

deviate significantly from unity. In principle, this can be due to: U-spin violation originating from  $m_s \neq m_d$  in the SM, and/or a drastic enhancement of the hadronic matrix elements of penguin operators in  $A_{U=0}$  either from long-distance dynamics in the SM or short-distance effects from sizeable NP. In the latter case, however, it can easily be seen that the enhancement of order  $\lambda^{-4} \sim \mathcal{O}(600)$  necessary to reproduce the pattern of BRs, at the same time clashes with the (still small) values for the direct CP asymmetries, which in such a case would be enhanced by the same factor, unless the strong phases of  $A_{U=0}$  and  $B_{U=1}$  were fine-tuned. Actually, we will find below that the simultaneous fit to  $\text{obs}_1$  and  $\text{obs}_2$  clearly fixes the strong-phase differences of the relevant interfering amplitudes in a scenario with broken U-spin to be large.

In the following, we are thus allowing for generic U-spin violation in the above decay amplitudes. In order to explain the measured BRs, we would have to accept U-spin violating effects as large as 50-60% on the amplitude level. In the naive factorization approach, such factors can largely be explained by the difference in decay constants ( $f_K/f_\pi$ ) and hadronic form factors ( $F(D \rightarrow K)/F(D \rightarrow \pi)$ ) each of which amounts to  $\mathcal{O}(20\%)$  corrections to the U-spin limit (recent lattice results<sup>2</sup> on these quantities can, for instance, be found in [30, 31]). As already mentioned, the observed BRs also require a significant strong-phase

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<sup>2</sup>We thank Ruth Van de Water for discussions pertaining to these.

difference which, together with the remaining amount of U-spin violation in the magnitude of the decay amplitudes, points towards essential non-factorizable long-distance effects in the hadronic matrix elements. Again, this comes as no surprise, as similar conclusions have been drawn from the analysis of non-leptonic  $B$ -meson decays (see e.g. [32–42] for an incomplete list of references), although the importance of non-factorizable contributions is appreciably less dramatic in  $B$ -meson decays due to the fact that the  $1/m_b$  expansion there is more efficient than a  $1/m_c$  expansion in  $D$ -meson decays.

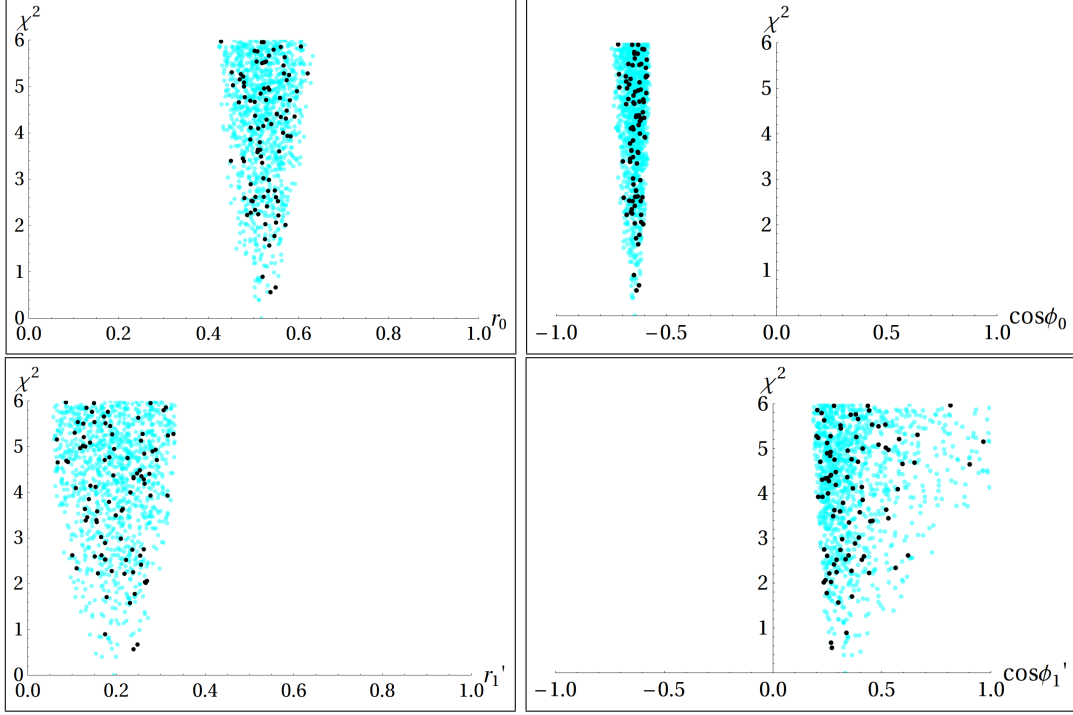
## 2.1 Including U-Spin Breaking

A non-zero strange-quark mass in the strong-interaction Hamiltonian gives rise to a new U-spin triplet operator that enters the hadronic interactions. In particular, this can turn  $U = 0$  operators in the weak effective Hamiltonian into  $U = 1$  amplitudes (denoted as  $\Delta B_{U=1}^{(\prime)}$ ) in the hadronic matrix elements and vice versa ( $H_{U=1}$  contributes to  $\Delta A_{U=0}$ ). The decomposition of the relevant decay amplitudes including (first-order) U-spin breaking then can be written as (see also [18, 23])

$$\begin{aligned}
\mathcal{A}[D^0 \rightarrow K^- \pi^+] &\equiv 2 V_{cs}^* V_{ud} (B_{U=1} - \Delta B_{U=1}^{\prime}) = 2 V_{cs}^* V_{ud} B_{U=1} \left[ 1 - r_1' e^{i\phi_1'} \right], \\
\mathcal{A}[D^0 \rightarrow \pi^+ \pi^-] &= (\lambda_d + \lambda_s) (A_{U=0} + \Delta B_{U=1}) + (\lambda_d - \lambda_s) (B_{U=1} + \Delta A_{U=0}) \\
&= B_{U=1} \left[ (\lambda_d + \lambda_s) \left( r e^{i\phi} + r_1 e^{i\phi_1} \right) + (\lambda_d - \lambda_s) \left( 1 + r_0 e^{i\phi_0} \right) \right], \\
\mathcal{A}[D^0 \rightarrow K^+ K^-] &= (\lambda_d + \lambda_s) (A_{U=0} - \Delta B_{U=1}) - (\lambda_d - \lambda_s) (B_{U=1} - \Delta A_{U=0}) \\
&= B_{U=1} \left[ (\lambda_d + \lambda_s) \left( r e^{i\phi} - r_1 e^{i\phi_1} \right) - (\lambda_d - \lambda_s) \left( 1 - r_0 e^{i\phi_0} \right) \right], \\
\mathcal{A}[D^0 \rightarrow K^+ \pi^-] &= 2 V_{cd}^* V_{us} (B_{U=1} + \Delta B_{U=1}^{\prime}) = 2 V_{cd}^* V_{us} B_{U=1} \left[ 1 + r_1' e^{i\phi_1'} \right]. \quad (2.7)
\end{aligned}$$

In the second equations of this parametrization, we have introduced various amplitude ratios and strong phases with respect to the originally leading  $B_{U=1}$  amplitude.

It is important to note that in the SM — or for that matter in many NP models — direct CP asymmetries in  $D^0 \rightarrow K^\mp \pi^\pm$  cannot arise due to the absence of penguin contributions in these decay modes. However,  $D^0$  and  $\bar{D}^0$  both can decay to the same final state  $K^\mp \pi^\pm$  which leads to interference between  $D^0$ - $\bar{D}^0$  mixing and the decay processes. Such a contribution though is expected to be extremely small (see below). On the other hand, if there are charged scalars with non-trivial flavour couplings and CP-odd phases (like, for instance in general models with extended Higgs sector), then direct CP asymmetries may arise in  $D^0 \rightarrow K^\mp \pi^\pm$ , too. The largish BR of about 3.8% for  $D^0 \rightarrow K^- \pi^+$  thus provides a valuable opportunity to search for a non-standard CP phase. LHCb and Super-B factories producing about  $10^9$  charm mesons should have a  $5\sigma$  reach of searching for CP asymmetries at the level of about 0.2% in this mode (similarly, for  $D^0 \rightarrow K^+ \pi^-$  with a BR of about  $1.5 \cdot 10^{-4}$  one can search for  $\mathcal{O}(1\%)$  CP asymmetries). Note also that this simple decay mode is of crucial importance in extracting the CKM angle  $\gamma$  from the  $B \rightarrow DK$  decays in the ADS [43] analysis, where traditionally one assumes no CP asymmetry in the subsequent D-decays. A confirmation of this assumption by direct experimental searches is therefore very valuable in any case.



**Figure 1.** Fit result for the amplitude parameters  $r_0$  and  $\cos \phi_0$  (upper row) and  $r'_1$  and  $\cos \phi'_1$  (lower row), determining the amount of U-spin breaking in  $D^0 \rightarrow P^+ P^-$  BRs. The generic points shown in light blue are consistent with the experimental constraints at the  $2\sigma$ -level and obey  $\chi^2 \leq 6$ . The black points denote a subset of points where the strong phase differences between  $A_{U=0}$  and  $\Delta A_{U=0}$ , as well as between  $B_{U=1}$  and  $\Delta B_{U=1}$  are assumed to be equal within a few percent,  $(\phi - \phi_0) = \{0, \pi\}$  and  $\phi_1 = \{0, \pi\}$ .

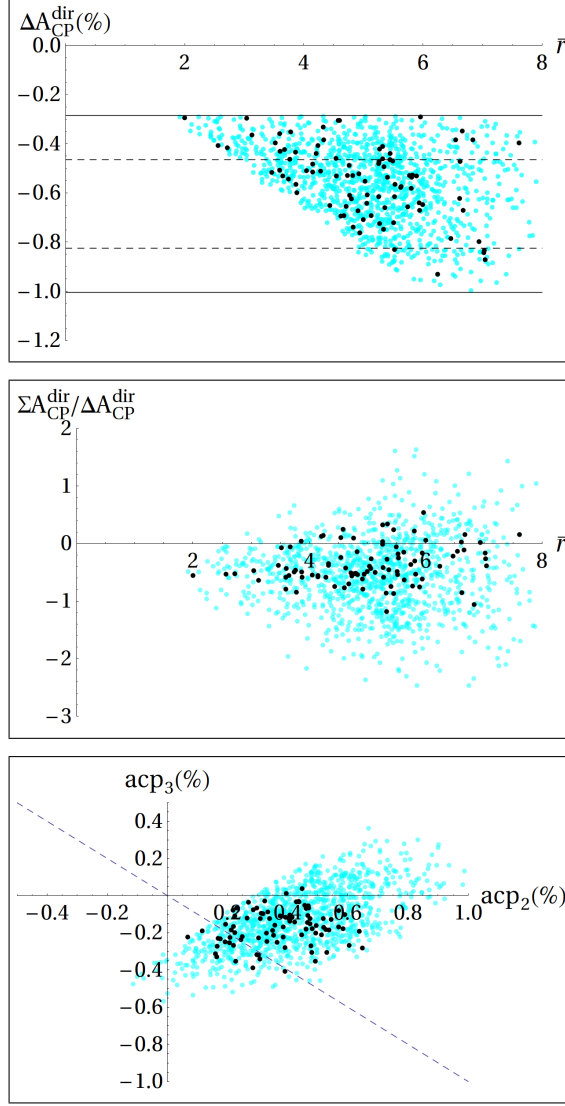
## 2.2 Phenomenological Constraints on Amplitude Ratios

In the following, we perform a fit to the 8 amplitude parameters ( $r, r_0, r_1, r'_1$  and  $\phi, \phi_0, \phi_1, \phi'_1$ ) to the 3 experimentally measured ratios of BRs in (2.4–2.6) and the difference of CP asymmetries in (1.5). We also take into account the fitted value [25] of the strong phase difference between the  $D^0 \rightarrow K^\pm \pi^\mp$  decays,  $\Delta\phi = 22.4^\circ \substack{+9.7^\circ \\ -11.0^\circ}$ . To this end, we generated random points which (i) lie within the  $2\sigma$  ranges for each experimental observable, and (ii) yield a total  $\chi^2$ -value of less than 6. We have allowed arbitrary strong phases while the magnitudes of the various amplitude ratios are considered in a conservative range  $|r_X| \leq 8$ . The result is illustrated in figs. 1,2.

From fig. 1, we observe that the parameters describing the U-spin breaking effects from the amplitudes  $\Delta A_0$  and  $\Delta B'_1$  are rather tightly constrained, with

$$r_0 \simeq 0.52, \quad \cos \phi_0 \simeq -0.64, \quad r'_1 \simeq 0.19, \quad \cos \phi'_1 \gtrsim 0.18.$$

The individual values for the magnitudes ( $r, r_1$ ) and phases ( $\phi, \phi_1$ ) related to the Cabibbo-suppressed operators are not fixed from the fit. A useful parameter to study the effect on



**Figure 2.** Fit result for difference of CP asymmetries  $\Delta A_{\text{CP}}^{\text{dir}}$  (top; horizontal lines indicate the  $1\sigma$  and  $2\sigma$  experimental constraints), and the ratio of the sum and difference of CP asymmetries (center) in  $D^0 \rightarrow K^+K^-$  and  $D^0 \rightarrow \pi^+\pi^-$  decays as a function of  $\bar{r} = \sqrt{r^2/2 + r_1^2/2}$ . The lower plot shows the correlation between the two asymmetries  $\text{acp}_3 = A_{\text{CP}}^{\text{dir}}(D^0 \rightarrow K^+K^-)$  and  $\text{acp}_2 = A_{\text{CP}}^{\text{dir}}(D^0 \rightarrow \pi^+\pi^-)$ , (the dashed line indicates the naive U-spin limit). Plot conventions as in fig. 1.

the direct CP asymmetries is given by the average

$$\bar{r} = \sqrt{r^2/2 + r_1^2/2}. \quad (2.8)$$

This is illustrated in fig. 2, where we have plotted the difference of CP asymmetries  $\Delta A_{\text{CP}}^{\text{dir}}$ , as well as their sum divided by the difference as a function of  $\bar{r}$ . The following interesting observations can be made:



- The effect of U-spin breaking from  $r'_1$  (entering the BRs for  $D^0 \rightarrow K^\pm \pi^\mp$ ) is relatively small as compared to the effect from  $r_0$  (entering the BRs for  $D^0 \rightarrow K^+ K^-$  and  $D^0 \rightarrow \pi^+ \pi^-$ ). Again, this can be partly understood in the framework of naive factorization, where in the former case the U-spin breaking in the  $D \rightarrow K(\pi)$  form factors tends to compensate the effect in the decay constants  $f_K(\pi)$ , whereas in the latter case, the two effects tend to add up.
- There is a clear correlation between  $\Delta A_{\text{CP}}^{\text{dir}}$  and the minimal value for the effective amplitude parameter  $\bar{r}$ . To reproduce the experimental  $2\sigma$ -range for  $\Delta A_{\text{CP}}^{\text{dir}}$ , one has to require  $\bar{r} \gtrsim 2$ . It remains to be seen whether such large values are consistent with our theoretical expectations, given our restricted knowledge on non-perturbative strong dynamics in time-like hadronic processes.
- The U-spin relation,  $\Sigma A_{\text{CP}}^{\text{dir}} = A_{\text{CP}}^{\text{dir}}(D^0 \rightarrow K^+ K^-) + A_{\text{CP}}^{\text{dir}}(D^0 \rightarrow \pi^+ \pi^-) = 0$ , receives corrections of the same order as  $\Delta A_{\text{CP}}^{\text{dir}}$  itself, or even larger (although the case  $\Sigma A_{\text{CP}}^{\text{dir}} = 0$  is not excluded). Consequently, the correlation between  $A_{\text{CP}}^{\text{dir}}(D^0 \rightarrow K^+ K^-)$  and  $A_{\text{CP}}^{\text{dir}}(D^0 \rightarrow \pi^+ \pi^-)$  can be quite different compared to the naive U-spin limit.
- The qualitative results for the BRs and CP asymmetries as a function of the amplitude ratios is well represented by a subset of parameters (indicated by the black points in figs. 1,2) where the strong phase differences between the amplitudes  $A_{U=0}$  and  $\Delta A_{U=0}$  (as well as between  $B_{U=1}$  and  $\Delta B_{U=1}$ ) are set approximately to zero or  $\pi$ .

### 2.3 Simplified Analysis of U-Spin Breaking

As we have seen above, the strong phase differences between individual  $U = 1$  (or  $U = 0$ ) amplitudes does not play an essential role for the analysis of direct CP asymmetries in  $D^0$  decays (they simply reflect the redundancy in the effectively 3-dimensional space of the constrained parameter space in the fit). To simplify the further analysis, we will therefore set

$$\phi_1 = (0, \pi), \quad \phi = (\phi_0, \phi_0 + \pi). \quad (2.9)$$

For the description of the BRs, we can also safely neglect the terms proportional to  $(\lambda_d + \lambda_s) \sim \mathcal{O}(\lambda^5)$ . With this approximation, the parameters  $r_0$  and  $\phi_0$  can be extracted from the observed ratios of BRs,  $\text{obs}_{1-3}$ . The constraint from  $\text{obs}_1$  alone translates into the inequalities,

$$\begin{aligned} 0.28 &\simeq 1 - \frac{2}{\sqrt{\text{obs}_1} + 1} \leq r_0 \leq 1 + \frac{2}{\sqrt{\text{obs}_1} - 1} \simeq 3.51, \\ \cos \phi_0 &\leq -\frac{\text{obs}_1 - 1}{\text{obs}_1 + 1} \simeq -0.53. \end{aligned} \quad (2.10)$$

Notice that these bounds already constrain the possible values for  $\text{obs}_2$  and  $\text{obs}_3$ . Including the average of  $\text{obs}_2$  and  $\text{obs}_3$ , the central values of  $r_0$  and  $\phi_0$  take values

$$r_0 \simeq 0.54, \quad \cos \phi_0 \simeq -0.69, \quad (2.11)$$

which are consistent with the previous fit within the uncertainties.<sup>3</sup>

Concerning the direct CP asymmetries, the constraints from  $\text{obs}_{1-3}$  alone cannot restrict the Cabibbo-suppressed amplitudes  $A_{U=0}$  or  $\Delta B_{U=1}$  which only provide a tiny ( $< 1\%$ ) correction to the BRs. Within our approximations, and assuming that all amplitude ratios are of  $\mathcal{O}(1)$ , we obtain

$$A_{\text{CP}}^{\text{dir}}(K^+K^-) - A_{\text{CP}}^{\text{dir}}(\pi^+\pi^-) \simeq \frac{8 \text{Im}[\lambda_d \lambda_s^*]}{|\lambda_d - \lambda_s|^2} \cdot \frac{(1 + r_0^2)(-r \sin \phi + r_0 r_1 \sin(\phi_0 - \phi_1))}{1 - 2r_0^2 \cos 2\phi_0 + r_0^4}, \quad (2.12)$$

together with

$$\frac{A_{\text{CP}}^{\text{dir}}[D^0 \rightarrow K^+K^-] + A_{\text{CP}}^{\text{dir}}[D^0 \rightarrow \pi^+\pi^-]}{A_{\text{CP}}^{\text{dir}}[D^0 \rightarrow K^+K^-] - A_{\text{CP}}^{\text{dir}}[D^0 \rightarrow \pi^+\pi^-]} \simeq -\frac{\text{obs}_1 - 1}{\text{obs}_1 + 1} \simeq -53\%. \quad (2.13)$$

The latter equation shows again that — as soon as U-spin violating effects are included — the direct CP asymmetries in  $D^0 \rightarrow \pi^+\pi^-$  and  $D^0 \rightarrow K^+K^-$  are no longer equal in magnitude. The particular value in (2.13) reproduces the central value of the trend apparent in fig. 2 (right); allowing for arbitrary strong phases, the effect can become even larger. The former eq. (2.12) states that the measured difference of direct CP asymmetries (considering the leading term in the Wolfenstein expansion) is a product of 3 terms,

$$\begin{aligned} f_{\text{weak}} &= 4 \text{Im} \left[ \frac{\lambda_d^* + \lambda_s^*}{\lambda_d - \lambda_s} \right] \simeq 2A^2 \lambda^4 \eta \approx 0.11\%, \\ f_{\Delta U} &= \frac{1 + r_0^2}{1 - 2r_0^2 \cos 2\phi_0 + r_0^4} \simeq 1.1 \\ f_{\text{strong}} &= -r \sin \phi + r_0 r_1 \sin \phi_0 \cos \phi_1. \end{aligned} \quad (2.14)$$

In order to achieve the central value of the experimentally observed number,  $f_{\text{strong}}$  should be about  $-5.3$ , which requires accordingly large values for  $r$  and  $r_1$ . More moderate values for  $r, r_1$  are possible if we consider the  $2\sigma$  range, only (as we have seen before). As the direct CP asymmetries scale linearly with both the amplitude ratios  $r$  and  $r_1$ , there is no preference for whether the original amplitude  $A_{U=0}$  or the effect of U-spin violation through  $\Delta B_{U=1}$  should be dominating the required value of  $f_{\text{strong}}$ , although the effect of  $r_1$  is somewhat diminished by the factor  $r_0 < 1$ .

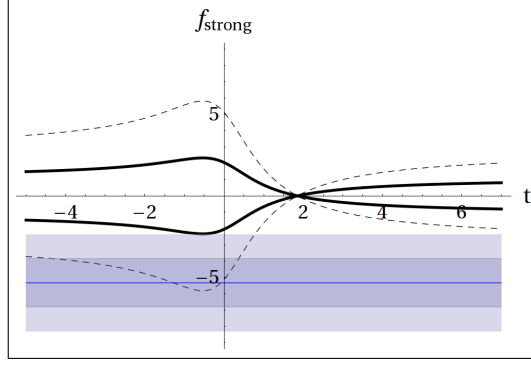
To illustrate the result, we consider the average of amplitude parameters  $\bar{r}$  together with

$$t \equiv \frac{r_1 \sin \phi_0 \cos \phi_1}{r \sin \phi} = \pm \frac{r_1}{r}. \quad (2.15)$$

In fig. 3, we plot the result for  $f_{\text{strong}}$  together with the experimentally preferred range for two values  $\bar{r} = \{2, 5\}$  as a function of  $t$ . As before, we can see that with  $\bar{r} = 5$  (dashed line) and for negative values of  $t$  the result falls comfortably into the experimental  $1\sigma$  range, whereas for  $\bar{r} = 2$  (solid line), the result is marginally consistent with the measurement at the  $2\sigma$  level.

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<sup>3</sup> The result of this procedure is similar to a recent analysis of  $SU(3)$  flavour-symmetry breaking in non-leptonic  $D$  decays considered in [18], where the authors neglected what would correspond to our parameter  $r'_1$  which has been motivated by dropping higher  $SU(3)$  representations in the effective Hamiltonian.



**Figure 3.** The function  $f_{\text{strong}}$ , determining the size of  $\Delta A_{\text{CP}}^{\text{dir}}$  in the SM, as a function of the amplitude ratio  $t$  for two different values of the averaged amplitude ratios,  $\bar{r} = 2$  (solid lines) and  $\bar{r} = 5$  (dashed lines), see eq. (2.15). The values necessary to recover the experimental  $1\sigma$  ( $2\sigma$ ) range in eq. (1.5) are shown in different shades of grey.

## 2.4 A Note on Mixing-induced CP Asymmetries

As described in eq. (1.2), apart from the direct CP asymmetry, the time-integrated CP asymmetry  $A_{\text{CP}}(f)$  in the decay of  $D^0$  to a given final state  $f$  also contains a part which is due to the interference of decay with mixing, the so-called mixing-induced CP asymmetry  $A_{\text{CP}}^{\text{ind}}$  which is defined as

$$A_{\text{CP}}^{\text{ind}} = -\frac{2x|R_f|(1+|R_f|^2|R_m|^2)}{(1+|R_f|^2)^2|R_m|} \sin \phi. \quad (2.16)$$

Here  $R_f = \frac{\bar{A}_f}{A_f}$  denotes the ratio of the amplitudes for a given decay and its CP conjugate,  $R_m = \frac{q}{p}$  gives the ratio of the parameters  $p, q$  in  $D^0$ - $\bar{D}^0$  mixing,  $x = \frac{\Delta M_D}{\Gamma_D}$  denotes the ratio of the mass difference and decay width in the  $D^0$ - $\bar{D}^0$  system, and the phase  $\phi$  denotes the argument of the function  $\lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f}$ . The present experimental bound on the  $D^0 - \bar{D}^0$  mixing parameters, i.e. the value of  $x$  and the phase and magnitude of  $R_m$  are given by [25],

$$x = (0.98_{-0.26}^{+0.24})\%, \quad \arg\left(\frac{q}{p}\right) = (-8.5_{-7.0}^{+7.4})^\circ, \quad |R_m| = 0.87_{-0.15}^{+0.17}. \quad (2.17)$$

For decay modes like  $D^0 \rightarrow K^+K^-, \pi^+\pi^-$ , which — in the SM — do not have interfering amplitudes with different weak and strong phases of comparable size, one has  $|R_f| \approx 1$  and  $\arg(R_f) \approx 0$ . Hence, the phase  $\phi$  will be purely induced by  $D^0$ - $\bar{D}^0$  mixing. In such cases  $A_{\text{CP}}^{\text{ind}}$  can be treated as a universal quantity which does not depend on the final state mesons. In particular, its effect will drop out in the difference of CP asymmetries,  $\Delta A_{\text{CP}}$ , apart from a term correcting for the finite experimental cut on the proper decay time, relative to the life-time associated to the individual decay modes (see e.g. [44]). We have checked that the presence of U-spin violating effects in  $A_{\text{CP}}^{\text{ind}}(K^+K^-)$  and  $A_{\text{CP}}^{\text{ind}}(\pi^+\pi^-)$  have a negligible numerical effect of the order  $\lesssim 10^{-5}$  on  $\Delta A_{\text{CP}}$ .

## 2.5 $\Delta A_{\text{CP}}^{\text{dir}}$ in the Presence of a Fourth Generation

In the 4G extension of the SM, the presence of the heavy  $b'$ -quark gives an extra contribution to the penguin operators, and it also modifies the CKM elements, such that  $\lambda_d + \lambda_s + \lambda_b = -\lambda_{b'} \neq 0$ . Both effects can be accounted for by including an additional  $U = 0$  operator proportional  $\lambda_{b'}$  in the effective Hamiltonian. The amplitudes in eq. (2.7) can then be generalized to the 4G case as follows,

$$\begin{aligned}\mathcal{A}[D^0 \rightarrow \pi^+ \pi^-] &= B_{U=1} \left[ (-\lambda_b) \left( r e^{i\phi} + r_1 e^{i\phi_1} \right) + (\lambda_d - \lambda_s) \left( 1 + r_0 e^{i\phi_0} \right) \right. \\ &\quad \left. - \lambda_{b'} \left( r_4 e^{i\phi_4} + r'_4 e^{i\phi'_4} \right) \right], \\ \mathcal{A}[D^0 \rightarrow K^+ K^-] &= B_{U=1} \left[ (-\lambda_b) \left( r e^{i\phi} - r_1 e^{i\phi_1} \right) - (\lambda_d - \lambda_s) \left( 1 - r_0 e^{i\phi_0} \right) \right. \\ &\quad \left. - \lambda_{b'} \left( r_4 e^{i\phi_4} - r'_4 e^{i\phi'_4} \right) \right],\end{aligned}\tag{2.18}$$

where  $r_4^{(\prime)}$  and  $\phi_4^{(\prime)}$  parametrize the contribution of the new  $U = 0$  operator and its  $U = 1$  counterpart from U-spin violation in the corresponding hadronic matrix elements. As before, we assume that the corresponding strong phases are related to the other  $U = 0$  and  $U = 1$  amplitudes. Then, the additional contribution to  $\Delta A_{\text{CP}}^{\text{dir}}$  can again be factorized,

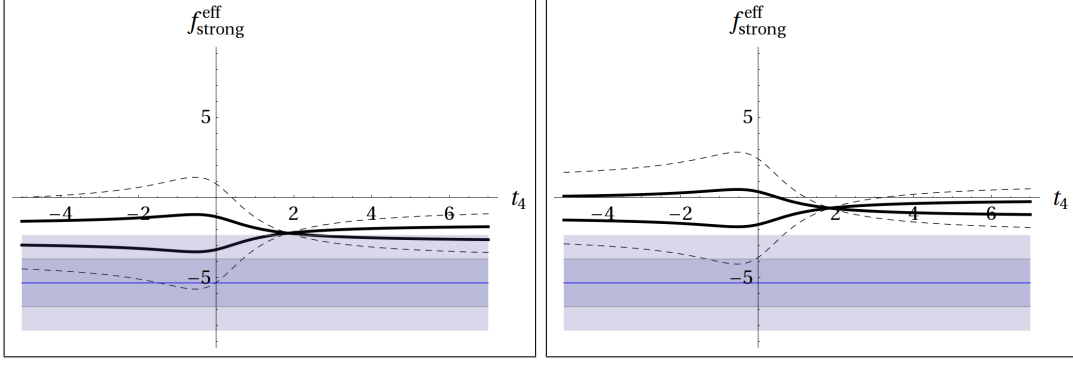
$$\begin{aligned}\Delta A_{\text{CP}}^{\text{dir}} &\simeq f_{\Delta U} \cdot \{ f_{\text{weak}} \cdot f_{\text{strong}} + f_{\text{weak}}^{4\text{G}} \cdot f_{\text{strong}}^{4\text{G}} \} \\ &\equiv f_{\Delta U} \cdot f_{\text{weak}} \cdot f_{\text{strong}}^{\text{eff}},\end{aligned}\tag{2.19}$$

with

$$\begin{aligned}f_{\text{weak}}^{4\text{G}} &= 4 \text{Im} \left[ \frac{\lambda_{b'}}{\lambda_d - \lambda_s} \right] \simeq \frac{2 \sin \theta_{14} \sin \theta_{24} \sin(\delta_{14} - \delta_{24})}{\sin \theta_{12}}, \\ f_{\text{strong}}^{4\text{G}} &= -r_4 \sin \phi_4 + r_0 r'_4 \sin \phi_0 \cos \phi'_4.\end{aligned}\tag{2.20}$$

Here, we have used the PDG-type parametrization for the 4G CKM matrix as in [45], and neglected higher-order terms in the Wolfenstein expansion. Notice that eq. (2.13) is still valid if our assumptions on the strong phases hold.

From the analysis of various flavour observables in the kaon and  $B$ -meson sector (see e.g. [45–48]), we know that the product of mixing angles  $\theta_{14}$  and  $\theta_{24}$  can be as large as  $\mathcal{O}(\lambda^4)$ , up-to  $\mathcal{O}(\lambda^3)$ , and therefore, in principle, can lead to an enhancement of the CP asymmetries by up to one order of magnitude as compared to the SM (where  $\sin \theta_{13} \sin \theta_{23} \sim \mathcal{O}(\lambda^5)$ ). However, it has also been found that for such large values of 4G mixing angles, the new CP phases  $\delta_{i4}$  are rather fine-tuned to values satisfying  $\delta_{14} \simeq \delta_{24}$  [8, 45]. This implies that the 4G CKM elements *cannot* lead to a substantial *parametric* enhancement (i.e. a suppression factor with less powers of the Wolfenstein parameter  $\lambda$ ) of CP asymmetries in  $D$  decays (contrary to a recent claim in [17], where — to our understanding — the phenomenological constraints on the 4G CP phases have not been taken into account properly). Still, the presence of the additional penguin operators can lead to a numerical enhancement which, however, is hard to quantify reliably without more detailed knowledge on the hadronic



**Figure 4.** The function  $f_{\text{strong}}^{\text{eff}}$ , determining the size of  $\Delta A_{\text{CP}}^{\text{dir}}$  in the 4G extension of the SM, as a function of the amplitude ratio  $t_4$  for two different values of the averaged amplitude ratios,  $\bar{r}_4 = 1$  (solid lines) and  $\bar{r}_4 = 3$  (dashed lines). The associated weak factor is set equal to the SM one,  $f_{\text{weak}}^{4G} = f_{\text{weak}}$ , and the SM amplitude ratios are set to  $r = r_1 = 2$ . The left (right) plot refers to a choice of strong phases where the two SM contributions  $r$  and  $r_1$  combine constructively (destructively) to a value of  $-2.2$  ( $-0.67$ ). The values necessary to recover the experimental  $1\sigma$  and  $2\sigma$  range in eq. (1.5) are shown in different shades of grey.

amplitude parameters. To illustrate the result, we define again

$$\bar{r}_4 \equiv \sqrt{\frac{r_4^2 + (r'_4)^2}{2}}, \quad t_4 \equiv \frac{r'_4 \sin \phi_0 \cos \phi'_4}{r_4 \sin \phi_4}, \quad (2.21)$$

and show in fig. 4 the result for  $f_{\text{strong}}^{\text{eff}}$  as a function of  $t_4$  for  $\bar{r}_4 = \{1, 3\}$ , while we fix  $f_{4G} = f_{\text{weak}}$  and  $r = r_1 = 2$ , for simplicity, and compare two different choices for the associated phases corresponding to constructive/destructive effects in the SM contribution (assuming an overall negative sign). One sees that  $\Delta A_{\text{CP}}^{\text{dir}}$  can receive some deviations from the SM with 3 generations, but without a quantitative theoretical estimate of the strong amplitudes, nothing more can be said.

## 2.6 Generic NP Explanation of $\Delta A_{\text{CP}}^{\text{dir}}$

The above results can easily be generalized to generic NP models, and the following statements can be made:

- Both, additional NP operators in the weak Hamiltonian with  $U = 0$  or  $U = 1$ , can contribute to the direct CP asymmetries.
- The new flavour coefficients can potentially enhance the corresponding factor  $f_{\text{weak}}^{\text{NP}}$  as compared to the SM. As a consequence, the observed value for  $\Delta A_{\text{CP}}^{\text{dir}}$  can be obtained with somewhat smaller values for the various hadronic amplitudes.
- Even in the presence of NP, in order to simultaneously explain the ratios of  $D^0$  decay BRs, while keeping the direct CP asymmetries sufficiently small, we have to require large U-spin violating effects. Therefore, in general, the direct CP asymmetries in  $\pi^+\pi^-$  and  $K^+K^-$  will not be equal in magnitude.

For more detailed NP analyses, see e.g. [21, 22].

Mode	BR	$A_{\text{CP}}$ in %	$5\sigma$ Reach
$D^+ \rightarrow K_S \pi^+$	$1.47 \times 10^{-2}$	$-0.52 \pm 0.14$ [25]	$1 \times 10^{-3}$
$D_s \rightarrow \eta' \pi^+$	$3.94 \times 10^{-2}$	$-6.1 \pm 3.0$ [49] $-5.5 \pm 3.7 \pm 1.2$ [25]	$0.7 \times 10^{-3}$
$D_s \rightarrow K_S \pi^+$	$1.21 \times 10^{-3}$	$6.6 \pm 3.3$ [49] $6.53 \pm 2.46$ [25]	$4 \times 10^{-3}$

**Table 1.** BRs and CP asymmetries in different charged  $D^+$  and  $D_s$  decay modes. The quoted (naive)  $5\sigma$  reach for the sensitivity on  $A_{\text{CP}}$  refers to  $10^9$  produced  $D^+, D_s$  mesons at LHCb or future Super-B factories.

## 2.7 Possibilities for Direct CP Searches in Charged Modes

Given that the current focus is on direct CP violation in neutral  $D^0$  decay modes, we note in passing that decays of charged meson,  $D^+$  and  $D_s$ , also offer many interesting and experimentally distinctive channels for such CP studies, with the advantage that  $D^0$ - $\bar{D}^0$  mixing is not involved. In table 1, we list a few 2-body decay modes of  $D^+$  and  $D_s$  mesons where a non-vanishing CP asymmetry has been reported with  $\gtrsim 2\sigma$  significance. With the foreseen statistics at LHCb and future Super-B factories, we find that interesting sensitivity to CP-violating effects in the SM or beyond, to the level of a few per mille, can be anticipated for these examples, too.

The current measurement of the CP asymmetry in the CA decay  $D^+ \rightarrow K_S \pi^+$  — within the present experimental uncertainties — is consistent with the SM expectation from  $K^0$ - $\bar{K}^0$  mixing (which is of order  $\epsilon_K \sim \lambda^3$ ), while the direct CP asymmetry is suppressed by a factor of  $\lambda^6$  and therefore negligible [50, 51]. NP contributions to the direct CP asymmetries of the order of several per mille could thus alter the SM prediction significantly which could be tested in the future. In this context, it would also be useful to tag on the flavour eigenstate in  $D^+ \rightarrow \bar{K}^0 \pi^+$  (or also  $D^+ \rightarrow \bar{K}^{*0} \pi^+$ ). In a similar fashion, in the SCS decay mode  $D_s \rightarrow K_S \pi^+$ , a contribution from  $K^0$ - $\bar{K}^0$  mixing is unavoidable, but in this case also penguin effects can contribute to  $A_{\text{CP}}^{\text{dir}}$  at the per-mille level, as shown in the preceding discussion. The current experimental central value is rather high, but only with a small significance of about  $2\sigma$ . Here too, the decay into the flavour state,  $D_s \rightarrow K^{(*)0} \pi^+$  deserves experimental attention. Finally, the CA decay  $D_s \rightarrow \eta' \pi^+$  is a pure tree with vanishing CP asymmetry in the SM. Evidently, if the current  $2\sigma$  hint for the latter decay mode gets verified, close to its current central value, that could be an important sign of NP.

There are many other modes of D and  $D_s$  which could be suitable for direct CP studies. Some examples of SCS modes involving penguins are:  $D^+ \rightarrow K^+ \bar{K}^{*0}, K^{*+} \bar{K}^0$ ;  $D^+ \rightarrow \phi \pi^+, \rho^0 \pi^+, \pi^+ \pi^0(\eta')$ ;  $D_s \rightarrow K^+ \phi(\eta'), K^0(K^{*0}) \pi^+$  and many more. There are also further CA modes (with no penguin contributions) such as  $D^+ \rightarrow \bar{K}^0(\bar{K}^{*0}) \pi^+$ ,  $D_s \rightarrow \phi \pi^+(K^+)$  etc. As mentioned previously, the SCS modes with penguins and with typical BRs of a few per mille should allow definitive CP searches of  $\mathcal{O}(0.5\%)$ , and for CA modes w/o penguins we could get to about 0.2%.

### 3 Insights from Non-Leptonic $B$ -Meson Decays

In this section, we are looking for a correspondence between the considered  $D^0 \rightarrow P^+ P^-$  modes and suitable non-leptonic  $B$ -meson decays. Obviously, exchanging the roles of up- and down-type quarks would lead us to consider a symmetry between  $u$  and  $c$ , in the following referred to as  $W$ -spin. Of course, we expect such a symmetry to be badly broken, and rather than use the symmetry relations themselves — for the sake of this paper — we would like to study the amplitude ratios in a *parametrization* based on  $W$ -spin (including its violation to first order), analogous to eq. (2.7). In particular, we would like to quantify the phenomenologically allowed values for the various amplitude ratios in such a case, which might give us some guide-line about what to expect for the corresponding  $D^0 \rightarrow P^+ P^-$  case.

With this in mind, we can repeat our previous analysis for the decays

$$\bar{B}_d^0 \rightarrow D_s^- \pi^+, D^+ K^-, K^- \pi^+, D_s^- D^+$$

in a straight-forward manner.<sup>4</sup> The relevant effective Hamiltonian, describing the  $b \rightarrow sq\bar{q}'$  transitions, can be decomposed as

$$H_{\text{eff}}(b \rightarrow sc\bar{u}) = - (V_{cb} V_{us}^*) H_{W=1}^{(W_3=-1)}, \quad (3.1)$$

$$H_{\text{eff}}(b \rightarrow sq\bar{q}) = \left( \frac{V_{ub} V_{us}^* - V_{cb} V_{cs}^*}{\sqrt{2}} \right) H_{W=1}^{(W_3=0)} + (V_{ub} V_{us} + V_{cb} V_{cs}) H_{W=0}, \quad (3.2)$$

$$H_{\text{eff}}(b \rightarrow su\bar{c}) = (V_{ub} V_{cs}^*) H_{W=1}^{(W_3=+1)}. \quad (3.3)$$

Notice that, in this case, the CKM elements scale as

$$\begin{aligned} \lambda_c &\equiv V_{cb} V_{cs}^* \simeq A \lambda^2, & V_{cb} V_{us}^* &\simeq A \lambda^3, \\ \lambda_u &\equiv V_{ub} V_{us}^* \simeq A \lambda^4 (\rho - i\eta), & V_{ub} V_{cs}^* &\simeq A \lambda^3 (\rho - i\eta), \end{aligned} \quad (3.4)$$

which changes the relative importance of the corresponding hadronic amplitude parameters for BRs and CP asymmetries in comparison with the U-spin analysis of  $D^0$  decays. The latter can be parametrized analogously to eq. (2.7),

$$\begin{aligned} \mathcal{A}[\bar{B}^0 \rightarrow D^+ K^-] &= 2 V_{cb} V_{us}^* B_{W=1} \left[ 1 - r'_1 e^{i\phi'_1} \right], \\ \mathcal{A}[\bar{B}^0 \rightarrow K^- \pi^+] &= B_{W=1} \left[ (\lambda_u + \lambda_c) \left( r e^{i\phi} + r_1 e^{i\phi_1} \right) + (\lambda_u - \lambda_c) \left( 1 + r_0 e^{i\phi_0} \right) \right], \\ \mathcal{A}[\bar{B}^0 \rightarrow D_s^- D^+] &= B_{W=1} \left[ (\lambda_u + \lambda_c) \left( r e^{i\phi} - r_1 e^{i\phi_1} \right) - (\lambda_u - \lambda_c) \left( 1 - r_0 e^{i\phi_0} \right) \right], \\ \mathcal{A}[\bar{B}^0 \rightarrow D_s^- \pi^+] &= 2 V_{ub} V_{cs}^* B_{W=1} \left[ 1 + r'_1 e^{i\phi'_1} \right], \end{aligned} \quad (3.5)$$

where for simplicity we have used the same notation for the amplitude ratios as for the U-spin analysis of  $D^0$  decays. As for the experimental input, we consider the four observables

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<sup>4</sup>A similar analysis could be performed for U-spin related modes, where the  $B_d$ -meson in the initial state is replaced by  $B_s$ , and/or the effective Hamiltonian for  $b \rightarrow sq\bar{q}'$  is replaced by the one for  $b \rightarrow dq\bar{q}'$ .

[49]

$$\begin{aligned}
\text{br}_1/\text{br}_2 &= \frac{\text{Br}[\bar{B}^0 \rightarrow D^+ K^-]/|\vec{p}_{DK}|}{\text{Br}[\bar{B}^0 \rightarrow K^- \pi^+]/|\vec{p}_{K\pi}|} \simeq 11.8 \pm 3.6, \\
\text{br}_3/\text{br}_2 &= \frac{\text{Br}[\bar{B}^0 \rightarrow D_s^- D^+]/|\vec{p}_{D_s D}|}{\text{Br}[\bar{B}^0 \rightarrow K^- \pi^+]/|\vec{p}_{K\pi}|} \simeq 536 \pm 62, \\
\text{br}_4/\text{br}_2 &= \frac{\text{Br}[\bar{B}^0 \rightarrow D_s^- \pi^+]/|\vec{p}_{D_s \pi}|}{\text{Br}[\bar{B}^0 \rightarrow K^- \pi^+]/|\vec{p}_{K\pi}|} \simeq 1.28 \pm 0.16,
\end{aligned} \tag{3.6}$$

and

$$\text{acp}_2 = A_{\text{CP}}^{\text{dir}}[\bar{B}^0 \rightarrow K^- \pi^+] \simeq -0.098 \pm 0.013. \tag{3.7}$$

From this we can perform a fit to the 8 real parameters  $(r, r_0, r_1, r'_1 \text{ and } \phi, \phi_0, \phi_1, \phi'_1)$ , where again we generate random points which fulfill the experimental constraints within at least  $2\sigma$  and lead to a total  $\chi^2$ -value less than 6. To reproduce the difference between the two tree decays  $\bar{B}^0 \rightarrow D^+ K^-$  and  $\bar{B}^0 \rightarrow D_s^- \pi^+$ , in principle, one can allow for two different classes of solutions, with either  $r'_1 > 1$  or  $r'_1 < 1$ . In the following, we will focus on the case  $r'_1 < 1$ , which would be the natural choice in the factorization approximation.

Despite the fact that we might expect W-spin to be badly broken, the parametrization is sufficient to reproduce the available experimental data. A comment is in order about the fine-tuning in the amplitude parameters which is necessary to suppress the BR for the decay  $\bar{B}^0 \rightarrow K^- \pi^+$  with respect to  $\bar{B}^0 \rightarrow D_s^- D^+$ . To quantify this effect, we have determined the box-counting dimension (bcd) of the fitted parameter space, following [53]. We found a bcd which is indeed somewhat smaller than the naive dimension, 4 (referring to 8 fit parameters minus 4 experimental constraints). While each individual contributing amplitude is basically unconstrained in the fit, it turns out that the result for the average

$$r_{\text{avg}} = \sqrt{\frac{r^2 + r_1^2 + r_0^2}{3}}.$$

is bounded from above and, at the same time, again sets the order of magnitude for the potential direct CP asymmetries. This is illustrated in fig. 5, where we show results for the direct CP asymmetry

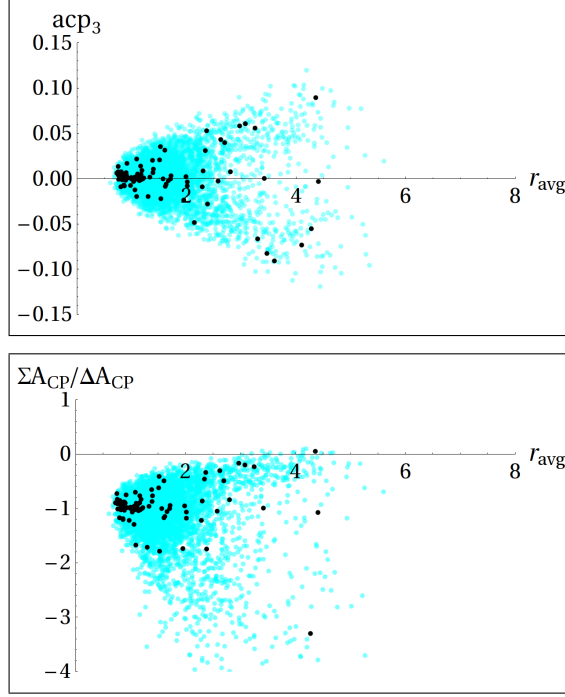
$$\text{acp}_3 = A_{\text{CP}}^{\text{dir}}[\bar{B}^0 \rightarrow D_s^- D^+] \quad (\text{not yet measured}), \tag{3.8}$$

and for the ratio  $\frac{\text{acp}_3 + \text{acp}_2}{\text{acp}_3 - \text{acp}_2}$  as a function of  $r_{\text{avg}}$ . In the approximation of universal strong phases in  $W = 0$  ( $W = 1$ ) amplitudes, the latter would be given by  $\frac{1 - \text{br}_3/\text{br}_2}{1 + \text{br}_3/\text{br}_2} \approx -1$ . The following observations can be made:

- The points generated by the fit satisfy

$$\begin{aligned}
0.6 &\leq r_{\text{avg}} \leq 6.0 && (\text{for } \chi^2 \leq 6), \\
0.8 &\leq r_{\text{avg}} \leq 5.3 && (\text{for } \chi^2 \leq 1).
\end{aligned} \tag{3.9}$$





**Figure 5.** Direct CP asymmetries as a function of  $r_{\text{avg}}$  (3.8) from a fit of W-spin parametrization to 4 observables in non-leptonic  $B^0$  decays. Plot conventions as in fig. 1.

- The maximal size of the (yet unmeasured) direct CP asymmetry  $|a_{\text{CP}3}|$  in  $\bar{B}^0 \rightarrow D_s^- D^+$  is given by  $\sim 12\%$  for  $\chi^2 < 6$  (restricting ourselves to values of  $\chi^2 < 1$  we would get slightly reduced values  $\sim 8 - 10\%$ ). Of course, smaller values for  $a_{\text{CP}3}$ , as expected in the factorization approximation, are not excluded in our approach. Experimental measurement of the CP asymmetries in  $\bar{B}^0 \rightarrow D_s^- D^+$  would be very useful in this respect.

Of course, we should keep in mind that this picture could change when higher-order W-spin breaking effects are taken into account. Still, we find this somewhat academic exercise useful in getting an idea about an upper bound on the generic amplitude ratios in non-leptonic  $B^0$  and  $D^0$  decays. Apparently, even for a badly broken symmetry like W-spin, the amplitude ratios in the considered  $B^0$  decays do not exceed a value of 5 – 6 or so. Naively translated to the  $D^0$  case, this implies that the amplitude ratios needed to explain the central value of  $\Delta A_{\text{CP}}^{\text{dir}}$  in the SM are at the upper limit of the acceptable (or expectable) range.

## 4 Conclusions

Let us summarize our main results:

- The ratios of BRs in  $D^0 \rightarrow \pi^+\pi^-, \pi^+K^-, K^+K^-$  require  $\mathcal{O}(1)$  U-spin violating effects. The required magnitude of U-spin violation can be understood (but not unambiguously predicted) from long-distance strong-interaction effects.
- The relative strong phase between the U-spin symmetric and U-spin violating contributions has to be large, too, which points towards essential non-perturbative hadronic rescattering effects. This is not surprising from experience on dealing with  $D$ -meson decays.
- As a consequence of U-spin violation, the direct CP asymmetries in  $D^0 \rightarrow \pi^+\pi^-$  and  $D^0 \rightarrow K^+K^-$  are no longer related to be equal in magnitude and opposite in sign (neither in the SM, nor in NP extensions).
- Within the SM, the hadronic matrix elements of  $c \rightarrow uq\bar{q}$  operators with highly Cabibbo-suppressed CKM factors should be enhanced compared to the leading operators by a factor of  $(3-5)$  in order to yield the observed central values for the direct CP asymmetries. Although we lack a comprehensive dynamical model to generate such an enhancement, there is no good reason to exclude the possibility of such numerical factors (the chiral enhancement of certain penguin operators in non-leptonic  $B$ -meson decays is a well-known example; indeed, in  $K$  decays such enhancements are even more pronounced). As a toy example, we have also studied the breaking of W-spin ( $u \leftrightarrow c$ ) in non-leptonic  $B^0$  decays, which is found to exhibit a very similar pattern of amplitude ratios and strong phases.
- Due to the presence of U-spin violation, NP contributions to the measured  $\Delta A_{\text{CP}}^{\text{dir}}$  are possible with both, NP operators having  $U = 0$  or  $U = 1$ .
- Considering the specific model of a SM extension by a fourth generation, we stress that large *parametric* enhancement of direct CP asymmetries (i.e. with less suppression in terms of the Wolfenstein expansion) in charm decays are not possible as a consequence of the tight constraints on the 4G mixing angles and CP phases from kaon and  $B$ -meson observables. Still, the additional short-distance contributions of the 4G quarks to the weak effective Hamiltonian allow for a numerical enhancement (but, in principle, also to a reduction) compared to the SM.
- From the experimental point of view, it should be worth looking into other non-leptonic  $D$ -meson decay modes which could be accessible to LHCb or Super-B factories. On the one hand, there can be modes like  $D^+ \rightarrow \phi\pi^+$ ,  $D_s \rightarrow \phi K^+$  which are induced by the same operators in the weak effective Hamiltonian as  $D^0 \rightarrow \pi^+\pi^-, K^+K^-$ , and therefore could be expected to yield direct CP asymmetries of similar magnitude. As an example, for  $D^+ \rightarrow \phi\pi^+$ , given the BR of about  $3.1 \cdot 10^{-3}$  (including the BR for the analyzing decay  $\phi \rightarrow K^+K^-$ ), with  $\mathcal{O}(10^9)$   $D$  mesons, a

$5\sigma$  reach for a 0.5% asymmetry is possible. On the other hand, one would like to constrain direct CP violation in tree-level decay modes such as  $D^+ \rightarrow \bar{K}^0(\bar{K}^{*0})\pi^+$ ,  $D_s \rightarrow \phi\pi^+(K^+)$  etc. in order to test against NP contributions in charged flavour transitions.

- Briefly, it may be worth pointing out that analogous  $D^0$  decay modes into light vector and pseudoscalar mesons ( $PV$ ) can be included, specifically  $K^{*\pm}K^\mp$ ,  $\rho^\pm\pi^\mp$ . It is readily seen that significant U-spin violation takes place: phase-space corrected BRs (similar to  $\text{obs}_1$  in eq. (2.5)) give 0.29 and 0.21, respectively. These modes can therefore be used to complement our understanding of the important issues related to direct CP violation in charm decays.

In conclusion, we have emphasized that the breaking of U-spin symmetry between strange- and down-quarks points towards large non-factorizable long-distance effects in non-leptonic  $D^0$  decays with large strong phases. As a consequence, a SM interpretation of the present data on direct CP asymmetries in  $D^0 \rightarrow P^+P^-$  is plausible. On the other hand, NP models with a constrained flavour sector, like models with a fourth fermion generation, can contribute with a similar magnitude, leading to a moderate enhancement (or reduction) compared to the SM.

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